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AN INVESTIGATION INTO THE CAUSATIVE MECHANISMS FOR EXPLOSIVE CYCLONE DEVELOPMENT OVER THE ATLANTIC

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AN INVESTIGATION INTO THE CAUSATIVE MECHANISMS FOR EXPLOSIVE CYCLONE DEVELOPMENT OVER THE ATLANTIC

A Trident Scholar Project Report

by

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Explosive cyclogenesis is defined as the rapid intensification of a marine cyclone at the rate of 24 mb in a 24 hour period (Sanders, 1980). Such cyclones produce very intense storms which result in gale-force winds, heavy precipitation, and severe sea states along the East Coast of the United States. Green (1988) suggested that an atmospheric inversion (or lid) may play an important role in the explosive development of marine cyclones. The atmospheric lid condition is present prior to and upwind of cyclone development.

This study examines three ERICA, the Experiment on Rapidly Intensifying Cyclones over the Atlantic, cases for the presence of the atmospheric lid condition. Results show that the lid condition was present 12-48 hours prior to explosive cyclone development in ERICA cases IOP 4 and 5, while the lid condition was not present in the control case, LOP 6P. Moreover, the prediction of explosive marine cyclones would be improved with the use of operational numerical weather prediction models, such as the Nested Grid Model, provided these models have adequate vertical resolution.

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I. INTRODUCTION

Major winter storms, characterized by heavy snow, gale-force winds, and violent sea states, often affect the east coast of the United States, from the Carolinas northward. These storms, known as explosive cyclones, are cold season, maritime disturbances with maximum frequency in January and February (Sanders, 1987). This phenomenon poses a serious threat to life and property along the coast as well as far offshore. Intense cyclones have disrupted commercial shipping, capsized oil rigs, damaged ocean liners and naval vessels, and have frequently hindered naval sea and air operations. Two historical instances of explosive cyclones include the storm that struck the oceanliner HMS Queen Elizabeth II (QE II) and the President's Day snowstorm which covered the Mid-Atlantic states with 60 cm of snow. Unfortunately, forecasters were unable to predict these storms accurately due to the rapidity of storm development, lack of understanding of the cyclone's physical processes, and lack of data over the ocean.

The extratropical cyclone (Fig. 1) is a closed counter-clockwise circulation about a low pressure center, (L), that forms outside of tropical latitudes. It develops along the polar front, which separates tropical and polar air masses. Sanders (1980) defined an explosively developing storm, or "bomb", as an extratropical cyclone whose central mean sea level pressure falls at least 24 mb (2.4 kPa) in a 24-hour

period.

Recently, there has been considerable research to iprove understanding of the processes responsible for the intensification of such storms at sea. The Genesis of Atlantic Lows Experiment (GALE) was a field study conducted from January to March 1986. The objectives of GALE were to imporve understanding of the physical processes of rapidly developing cyclones, describe the airflow and moisture patterns, and develop and test numerical models for the prediction of rapidly intensifying East Coast storms (Dirks, 1988). A second major project, the Experiment on Rapidly

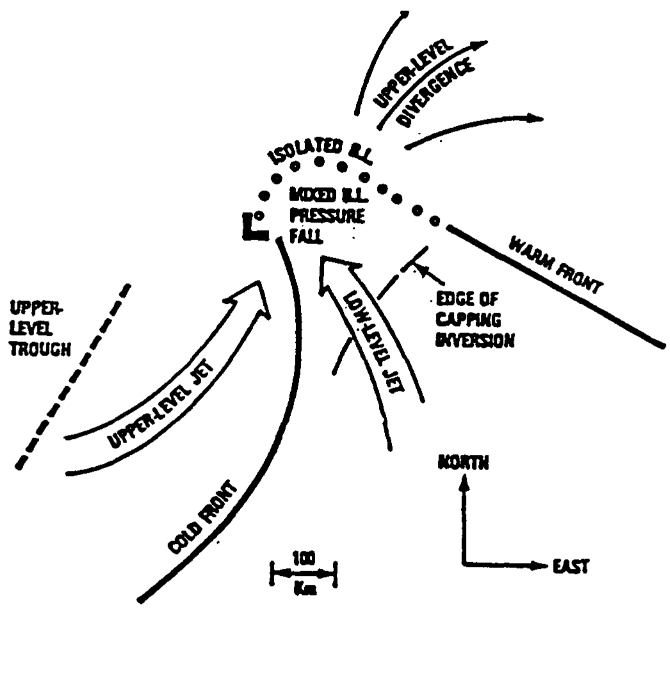

Figure 1. Schematic of an extratropical cyclone. The surface low pressure center is designated by L. (taken from Hadlock, 1988)

Intensifying Cyclones over the Atlantic (ERICA), was designed to determine the physical mechanisms and processes which can account for the wintertime phenomenon of explosively developing storms at sea (Hadlock, 1988). These projects provide very extensive data sets which are more complete than routine observations. These data sets allow for better analysis and increased probability of discovering the atmospheric causes for these cyclones.

A. REVIEW OF PAST STUDIES

The QE II storm (10-11 September 1978) and the President's Day Snowstorm (18-19 February 1979) are two extreme examples of meteorological "bombs" as defined by Sanders' criteria. Despite the existence of surface buoys and numerous mobile ships in the North Atlantic, real-time weather analyses and numerical prognoses performed poorly in detecting the intensity and tracks of these storms. As a result, many lives were endangered and millions of dollars in property damage occurred. It was the damage and devastation that resulted from these cyclones which sparked scientists to take an active interest in the study of explosive marine cyclones. Since Sanders first defined the "bomb", considerable research has been done, and many processes were studied. However, scientists continue to investigate explosive marine cyclones in hopes of answering the remaining questions regarding their development and

processes.

Explosive cyclogenesis, the process whereby a cyclone develops rapidly as defined by Sanders' criteria, is viewed as a scale interaction problem in which both synoptic-scale and mesoscale processes play important roles. The synoptic-scale trough-ridge patterns provide the general dynamical environment in which cyclogenesis is initiated and maintained (Dirks,1988). However, the topographical features along the east coast of the United States, including the Appalachian Mountains, the warm waters of the Gulf Stream, and the largest coastal lagoonal system in the United States play an important role in the process of cyclogenesis along the mid-Atlantic coastal region (Lee, 1991).

According to Bosart (1986), baroclinic instability, which results from strong meridional temperature gradients in the troposphere, is probably the dominant mechanism for development of most Atlantic bombs. Moreover, sensible and latent heat fluxes and cumulus convection also may be important processes in triggering explosive development (Manobianco, 1989). Sanders (1986) found that distinct 500-mb vorticity maxima were associated with bombs observed from at least 36 hours prior to and 24 hours subsequent to explosive deepening of cyclonic storms. An upper-level trough with embedded jet streaks provides a source of vorticity, upper-level divergence, and associated upward

vertical motion. A lower-level jet enhances moisture transport and provides the lifting mechanism for developing precipitation systems while it increases warm air advection at low levels (Dirks,1988).

As cold continental air outbreaks move over the warmer sea surface of the Gulf Stream, oceanic latent heat fluxes accelerate the low-level response to upper-level forcing. These fluxes destabilize the atmosphere near the center of the developing storm, thus increasing the conditional instability and potential for deep convection. Sanders (1980) found that explosive cyclogenesis frequently occurs near the strongest sea surface temperature (SST) gradients. Roebber (1984) added that the positions of explosive cyclone formation are predominantly associated with the warm Gulf Stream Current.

Despite considerable research surrounding the phenomena of explosive cyclogenesis, scientists are still unable to predict such storms accurately. The lack of data, in terms of both spatial and temporal resolutions, available in oceanic regions is a strong contributor to the failure of explosive cyclone forecasts. However, the extensive data sets of the GALE and ERICA studies can provide valuable insight into the processes contributing to explosive cyclogenesis. Both of these field experiments focused on the problem of the lack of available data over the water, by enhancing the conventional observational network both in

space and in time and by implementing the use of aircraft dropwinsondes and drifting buoys.

B. PURPOSE OF CURRENT INVESTIGATION

Since numerical forecasts still dramatically underpredict explosive marine cyclones both in frequency and intensity, Green (1988) posed a hypothesis that an atmospheric lid may lead to and be a recognizable precursor for the "bomb's" rapid and intense deepening. Using data from the GALE experiment, Green (1988) tested his hypothesis on several marine cyclones.

The atmospheric lid is a capping inversion, located in the lower to middle troposphere, which forms a moist marine boundary layer. It develops when mid-tropospheric, dry continental air advects over a maritime surface layer. The air above the lid is characterized by a conditionally unstable lapse rate and a sharp decrease in dew-point temperature. Below, the lid traps moisture from the evaporation of ocean water at the air-sea interface in the marine boundary layer. In the stable marine boundary layer, the effects of evaporative processes and sensible heat exchange are confined to the lower troposphere (Green, 1988). The accumulation of moisture adds to the Convective Available Potential Energy (CAPE), a measure of the energy that can be released to aid storm development. At higher CAPE values, the possibility of deep convection increases.

This convection is a necessary ingredient for any storm to develop, whether it be synoptic scale or mesoscale. However, the atmospheric lid actually inhibits convection from occurring. When the energy is released from under the inversion, through the process of underrunning or the result of large scale lifting (Carlson, 1989), the moist air becomes unstable above the lid, and resulting vertical motion provides additional vigor to storm growth (Green, 1988).

This study will test Green's hypothesis, the role of the atmospheric lid in explosive marine cyclones, utilizing the recently compiled data from the ERICA field experiment. The Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) is part of the Office of Naval Research Marine Meteorology Accelerated Research Initiative's Heavy Weather at Sea Program. ERICA consists of two interacting components, theoretical analysis and field measurements, conducted during the winter months of 1988 (Hadlock, 1988). During the ERICA field project, extensive meteorological data sets were taken during eight observation periods capturing extratropical marine cyclones. The synoptic and mesoscale analysis of data from research aircraft, dropwinsondes, land-based rawinsondes, ship, buoy, and satellite observations provided the first opportunity to document the evolution of mesoscale cyclone structure during explosive maritime cyclogenesis.

This study will test Green's hypothesis on the recently compiled ERICA data. The presence of the atmospheric lid will be examined for two explosive ERICA cases, IOP's[1] 4 and 5 as well as a non-explosive case, LOP[2] 6P, for comparison. The intent is to determine if Green's hypothesis is a critical factor in explosive cyclogenesis, which might be used as a predictor for this phenomenon.

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[1]IOP is an acronym for Intensive Observation Period.

[2]LOP is an acronym for Limited Observation Period

II. METHODOLOGY

Carlson and Ludlam (1968) first presented the conceptual model of the atmospheric lid. According to their model, topography, surface heating, and large scale weather patterns can produce lower tropospheric temperature inversions between 850 and 500-mb. These inversions, or lids, suppress the release of latent instability below the lid which leads to severe cumulus convection. Carlson (1983) continues that latent instability is released through erosion of the lid, vertical motion, and "underrunning". Underrunning occurs when the air actually moves horizontally out from under the lid. The energy released from under an atmospheric lid may be responsible for enabling a marine cyclone to develop explosively.

Currently, the United States National Weather Service utilizes the "lifted index" (LI) as a measure of latent instability of the lower troposphere. However, Carlson (1980) introduced the Lid Strength Index (LSI), which was developed to quantify the restraining effect of the lid on cumulus convection. Carlson believes that these lids are critical to convection, for even when lifted indices are favorable for convection, thunderstorms sometimes fail to occur. Green adopted Carlson's lid strength theory and its effect on intense thunderstorms and adapted it to the study of marine cyclones which are much larger scale atmospheric disturbances than thunderstorms. In this study, Carlson's

LSI will be used as a parameter for comparison of lid strengths during explosive marine cyclones.

The Lid Strength Index (Fig. 2) is divided into two terms, the lid strength term and the buoyancy term. The lid strength term, expressed by Eq (1), is a measure of the strength of the inversion and is very similar to the negative buoyancy area on a vertical temperature profile:

$$\text{lid strength} = (\theta_{sw1} - \theta_w), \qquad \text{Eq (1)}$$

where (θ_{sw1}) is the saturation wet-bulb potential temperature at the warmest point in the inversion, and (θ_w) is the mean wet-bulb potential temperature of the lower 50-mb of the sounding. The buoyancy term, Eq (2), is virtually

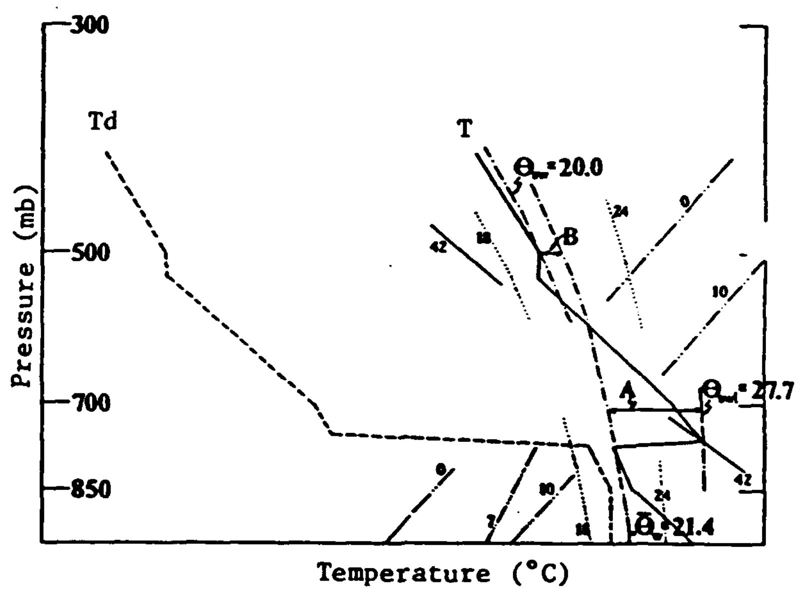


Figure 2. Schematic lid sounding on a skew T-log P diagram. The vertical temperature profile is indicated by the solid line (T) and that of the dewpoint by the dashed line (T_d). (Taken from Carlson, 1987)

the same as the lifted index and represents the positive buoyancy area on the temperature sounding:

$$\text{buoyancy term} = (\theta_{sw5} - \theta_w), \qquad \text{Eq (2)}$$

where (θ_{sw5}) is the saturation wet-bulb potential temperature at 500-mb, and (θ_w) is the mean wet-bulb potential temperature of the lower 50-mb of the sounding. The Lid Strength Index is found by summing the two equations (Carlson, 1987).

A positive LSI value indicates an unstable boundary and/or the presence of an atmospheric lid. If a strong lid condition exists upstream of the region of latent heat release, explosive development can occur when the moist air trapped below the lid is allowed to ascend over the low pressure center (Green, 1988).

In the current investigation explosive cyclones captured during two Intensive Observational Periods (IOP) of the ERICA field project were examined for the presence of the atmospheric lid. Green (1988) found the lid to be present 12-36 hours prior to rapid storm development and located upstream of where explosive deepening occurs. Therefore, rawinsonde data from mid-Atlantic stations were examined from up to 48 hours prior to explosive development to 36 hours after. In addition, aircraft dropwinsonde data over the western Atlantic were also studied. However, often this data source was available only during the IOP which

often did not commence until 6 hours before rapid development began. In examining the soundings, first the presence of a temperature inversion in the mid-tropospheric levels had to be verified. If the inversion existed coincident with a rapid moisture decrease, then lid strength and buoyancy terms were calculated using interpolated sounding values to get an LSI value. In addition, the lid terms were calculated using software developed by Carlson to verify hand-calculated results. Through the calculation and comparison of LSI values for both explosive and non-explosive cases of cyclogenesis, Green's hypothesis can be verified.

III. SYNOPTIC DISCUSSION

A. IOP 4

One of the most intense extratropical marine cyclogenesis events of the century took place in the western Atlantic Ocean 3-5 January 1989. The "Dream Storm" occurred during Intensive Observational Period four (IOP 4) of the ERICA field program. The following synoptic analysis discusses the primary meteorological features affecting the East Coast of the United States from 0000 UTC 2 January to 0600 UTC 5 January 1989.

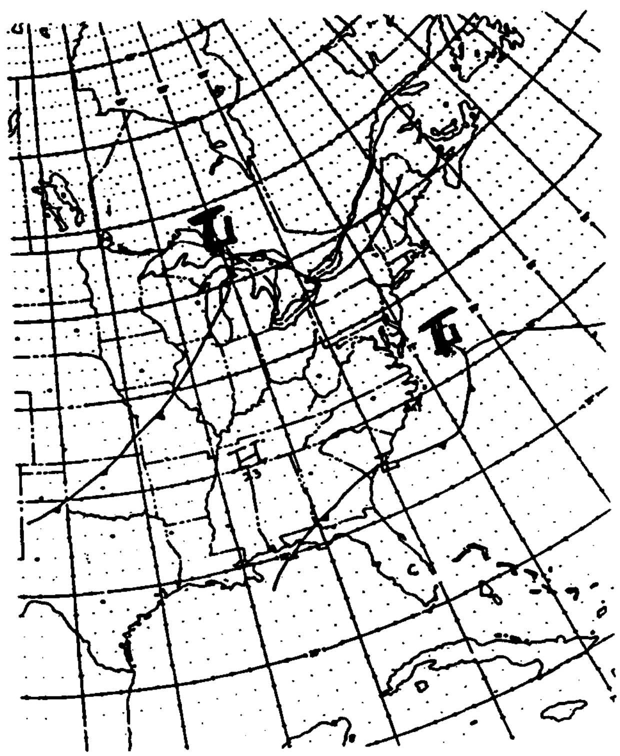


Figure 3. Surface analysis (0000 UTC 2JAN89) denoting major frontal systems and low (L) and high (H) pressure centers with central pressure value abbreviated (e.g. 05=1005 mb).

At 0000 UTC 2 January, two major systems (Fig. 3) occur over the eastern third of North America. The first surface low is intensifying off the Atlantic seaboard just east of Cape Hatteras, NC. The central pressure of the storm is 1005 mb, and a warm front extends southeastward while a trailing cold front runs from the low pressure center back through Georgia and the panhandle of Florida. The second cyclonic storm, with a central pressure of 1008 mb, lies just north of the Michigan peninsula. Associated with this low pressure center is a warm front extending from the low eastward over the Great Lakes and up into New England. By 0000 UTC on 3 January, the system (Fig. 4) offshore has

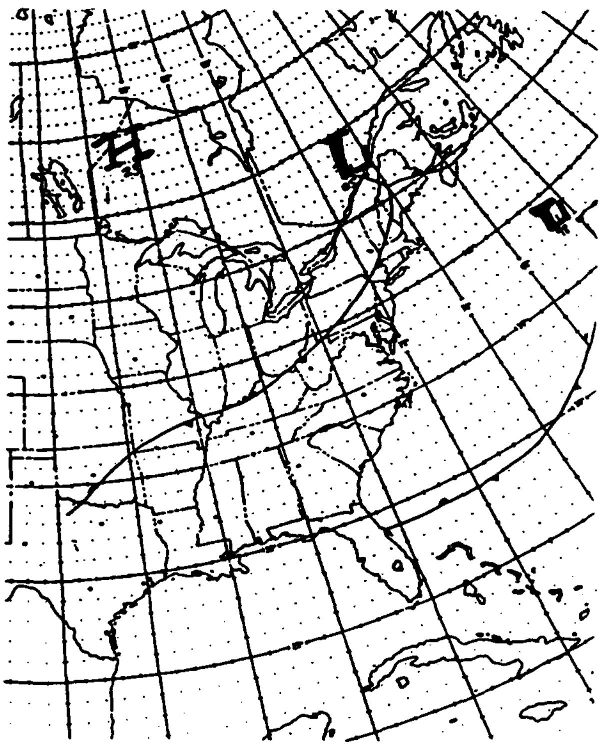


Figure 4. Surface analysis (0000 UTC 3JAN89)

tracked east-northeast to a position 38.5 N, 62 W and continues to deepen to 998 mb. The low of the second system, now 1005 mb, has moved to the northeast into the Canadian provinces. The associated cold front extends to the south through New England and westward to the Ohio River valley. Over the next 12 hours the Atlantic disturbance located off Nova Scotia has continued to intensify (984 mb) while the frontal system along the East Coast has rapidly dissipated (Fig. 5). A low pressure trough extends from the Great Lakes across Illinois and southward, and a stationary

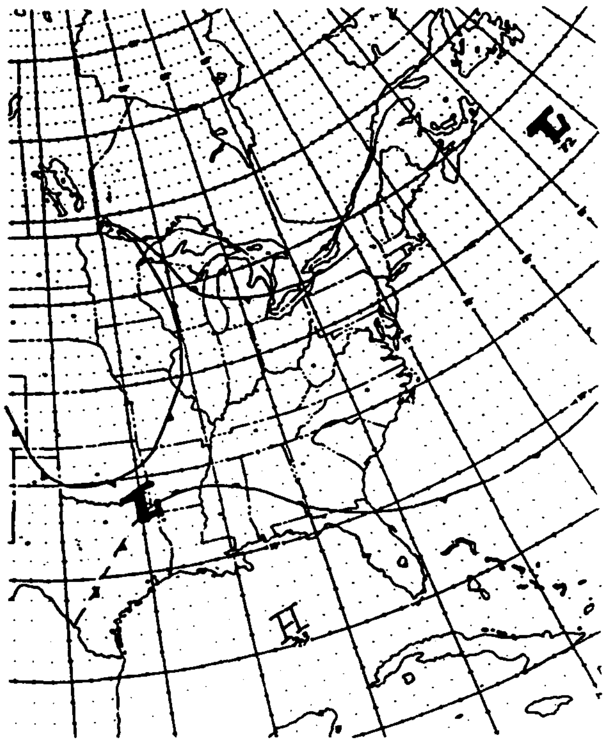


Figure 5. Surface analysis (1200 UTC 3JAN89)

front lies east-west over the Great Lake States and north-south west of the low pressure trough. At 2100 UTC on 3 January, the low pressure center (Fig. 6) over the North Atlantic has pushed farther north to 45 N and deepened to 965 mb. The low pressure trough present over mid-America has moved eastward, and three low pressure centers have developed along this line, ranging from north of Lake Ontario south to Virginia. The low over Kentucky shows an associated low pressure trough extending east across Maryland and out into the Atlantic. From this trough, the low pressure center associated with the "dream storm" of IOP 4 develops.

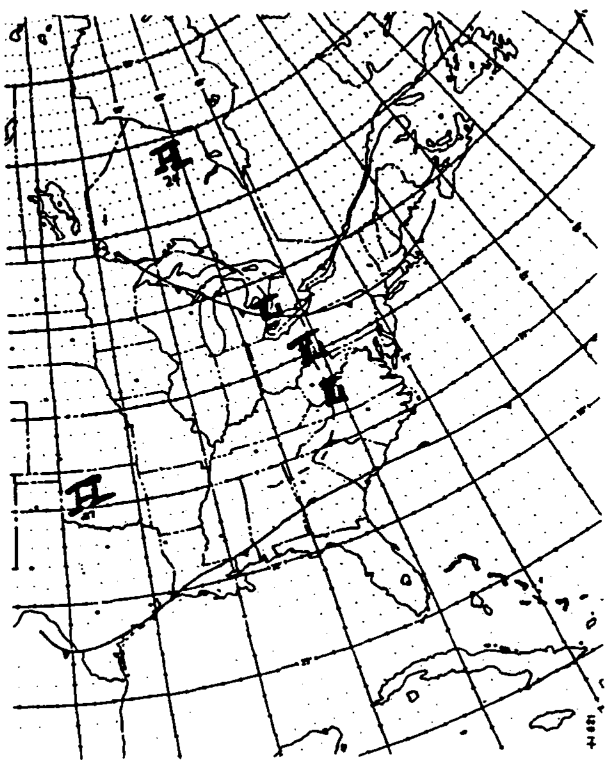


Figure 6. Surface analysis (2100 UTC 3JAN89)

At 0000 UTC on 4 January, an incipient extratropical marine cyclone (Fig. 7) is situated east of Cape Hatteras, with a central sea-level pressure of 996 mb. The low has a warm front extending east from the center and a trailing cold front that extends southwest over the Carolina seaboard, through Georgia, and along the Gulf Coast. A secondary low is located over Virginia and has an associated front projecting southward into northern Georgia.

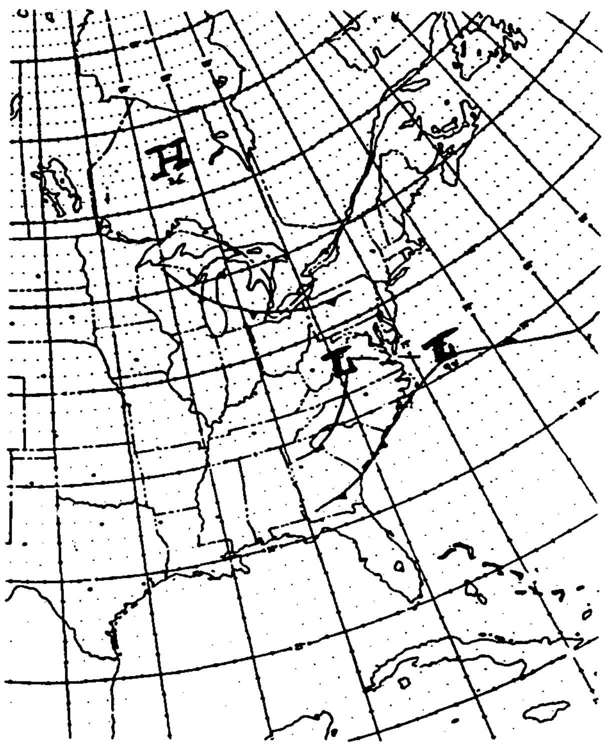


Figure 7. Surface analysis (0000 UTC 4JAN89)

The cyclone continued to move northeastward along the warm side of the Gulf Stream current where it explosively developed, with the central sea-level pressure decreasing from 996 mb to 936 mb, an incredible 60 mb in 24 hours (Fig. 8a,b). Figure 9 shows the complete track of that cyclone over the Atlantic. The cyclone can be detected in a satellite image (Fig. 10) by a comma-shaped cloud, a prominent feature common to extratropical cyclones (Bond, 1991). In addition, the extreme convective activity is evidenced by the high cloud tops present in the image. "Bomb" development was enhanced by a strong jet stream with a wind speed maximum of nearly 90 m/s upstream of the surface cyclone, and a 500-mb baroclinic zone with a

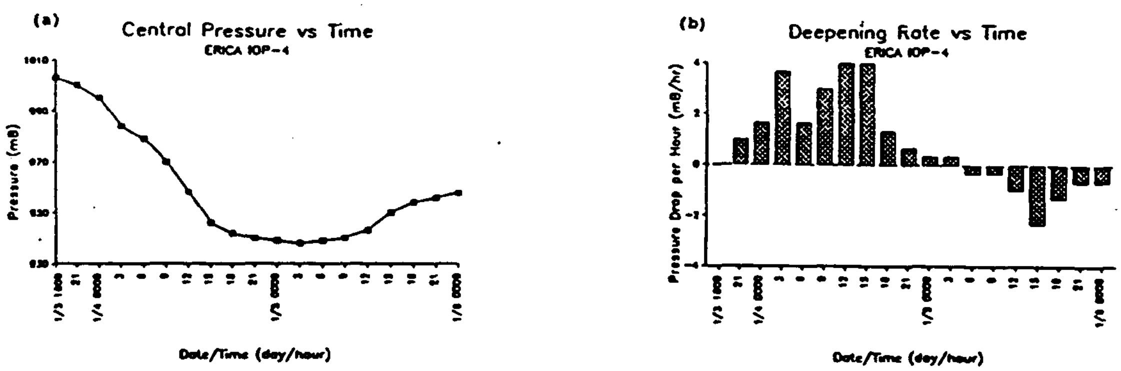


Figure 8. a) Central pressure (mb) vs time
b) Deepening rate (mb/3hr) vs time for IOP 4

temperature gradient of 18 C in 500 km (Donall, 1991). Between 0000 UTC and 0900 UTC 5 January (Fig. 11), the mature cyclone began to dissipate in the North Atlantic off the coast of the Canadian Maritime provinces as the central pressure increased from its minimum to 955 mb.

Why did this storm experience such amazing intensification over such a short time? What role did the lid condition play in the development of this marine cyclone? These questions will be explored in Chapter 4.

Figure 9. Track of IOP 4 cyclone

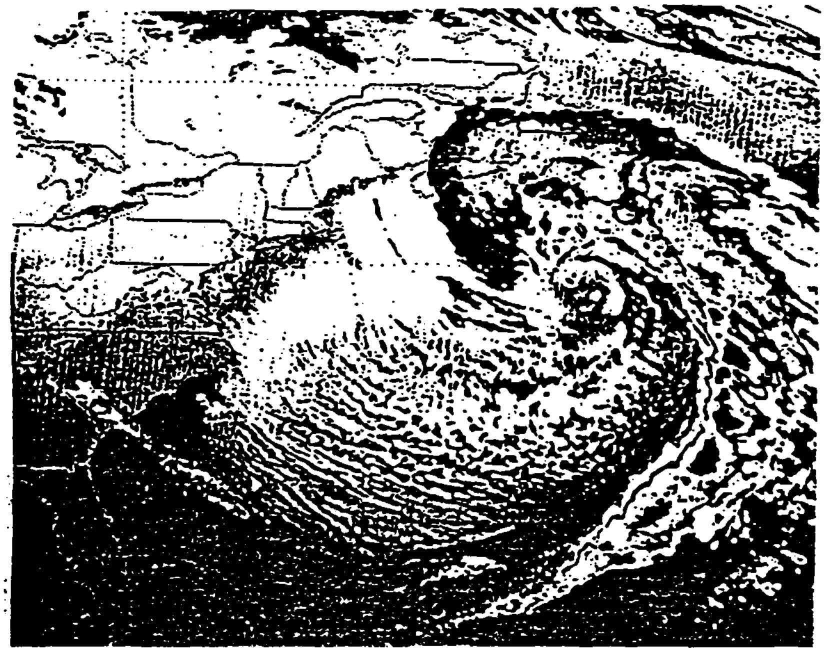


Figure 10. Satellite image 1200 UTC 4JAN89 showing a distinctive comma-shaped cloud over the Atlantic Ocean. (taken from Kreitzberg, 1990)

Figure 11. Surface analysis (0900 UTC 5JAN89)

B. IOP 5

A second explosive marine cyclone was captured 19-20 January 1989 during IOP 5 of the ERICA field project. This cyclone has been labeled the "Sleeper" due to delayed rapid deepening. The following synoptic analysis will discuss the meteorological systems affecting the eastern United States and the western Atlantic from 0000 UTC 17 January to 1800 UTC 20 January 1989.

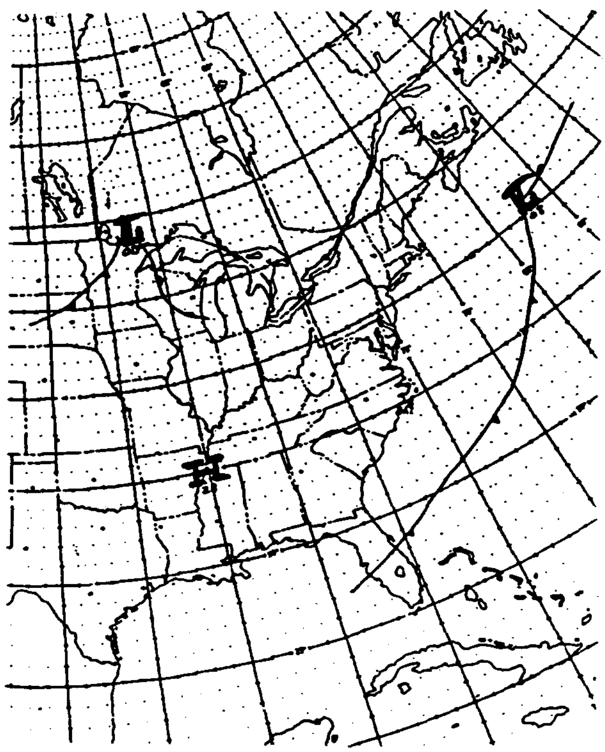


Figure 12. Surface analysis (0000 UTC 17JAN89)

At 0000 UTC 17 January (Fig. 12) two low pressure systems are present in the eastern third of North America. The first (1008 mb) located in the Atlantic east of New

England. The associated cold front extends southward through northern Florida. A second low with a central pressure of 1000 mb lies north of Minnesota with a trailing cold front and a warm front extending southeastward through the Great Lakes region. By 1200 UTC 17 January (Fig. 13) the Atlantic cyclone has moved well to the northeast and is dissipating. The second surface low has tracked east, now lying to the northeast of the Michigan Peninsula, and has intensified to a central pressure of 996 mb. The associated warm front sweeps south through New England while the cold

Figure 13. Surface analysis (1200 UTC 17JAN89)

front wraps westward across the upper Midwest. The south Atlantic states are under a wide region of high pressure. Over the next 12 hours (Fig. 14) the surface low, with a central pressure 1004 mb, has moved east to a position over Maine. The warm front lies east into the Atlantic while the cold front runs south through New England and then extends westward where it turns stationary over the upper Midwest. The high pressure over the southern states has begun to weaken. At 0600 UTC 18 January the New England system continues to weaken, now 1010 mb, but a second low pressure center has developed along the frontal wave in the upper

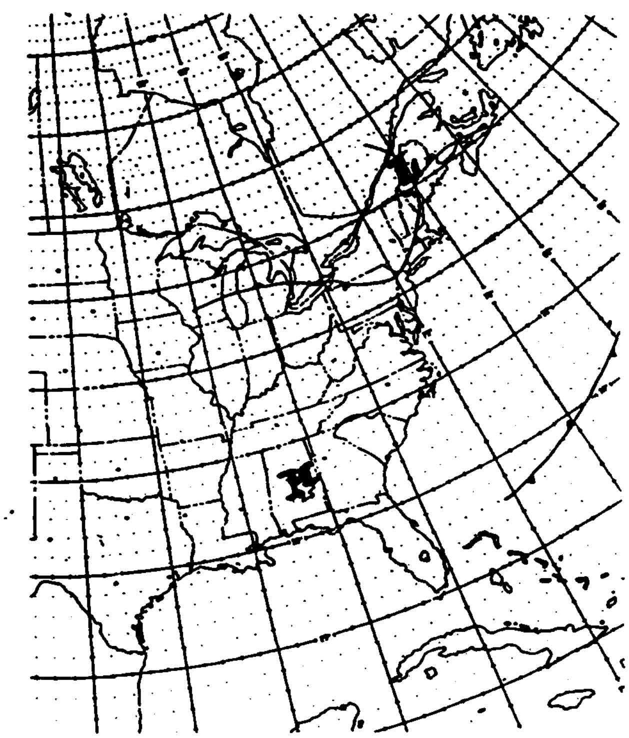


Figure 14. Surface analysis (0000 UTC 18JAN89)

Midwest. This cyclone, with a central pressure of 1009 mb, has a cold front extending southward to Texas. In addition, a region of low pressure has appeared in the Atlantic east of Cape Hatteras, NC. However, this low does not appear as a closed center and exhibits a pressure as high as 1023 mb.

At 0300 UTC 19 January (Fig. 15) the surface analysis shows the first low pressure system associated with IOP 5. The central pressure is 1010 mb and is located over the Atlantic directly east of the Delmarva peninsula. Due to a

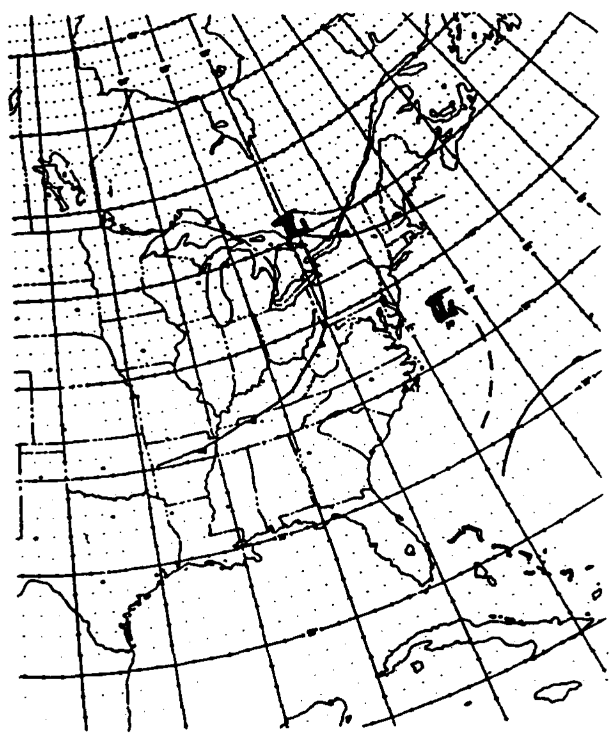


Figure 15. Surface analysis (0300 UTC 19JAN89)

blocking high over the eastern portion of Canada, the system previously located over Lake Michigan has continued to track in an eastwardly direction and maintains a central pressure of 1006 mb. The associated cold front extends southward, affecting the entire eastern third of the nation. The presence of high cloud tops and developing cumulus clouds over the western Atlantic associated with the low off the coast can be seen with the aid of satellite imagery (Fig. 16). At 0600 UTC 19 January (Fig. 17) a secondary low (1012 mb) has developed offshore of Cape Hatteras in the low

Figure 16. Satellite image 0300 UTC 19JAN89
(taken from Kreitzberg, 1990)

pressure trough of the IOP 5 low whose central pressure remains a high 1006 mb. The system over New England continues to track slowly to the east and weaken.

Over the next nine hours the "Sleeper" cyclone in the Atlantic has awakened and has begun to intensify. The IOP 5 cyclone has entered the occlusion stage of development with a central sea-level pressure of 1000 mb. In most cases, occlusion would mark the end of rapid deepening. However, the IOP 5 cyclone receives energy from the secondary low as it "catches up" with the cyclone. Rather than dissipate, the cyclone uses this additional energy to intensify.

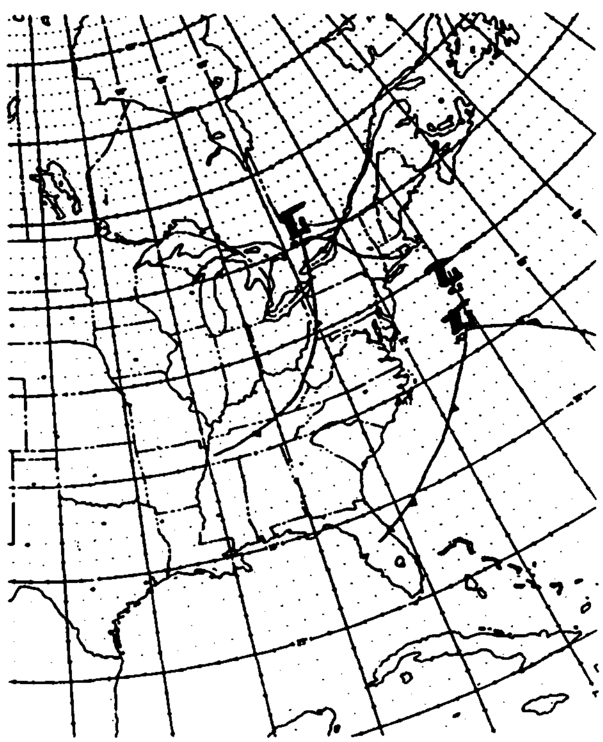


Figure 17. Surface analysis (0600 UTC 19JAN89)

From 1500 UTC 19 January to 1200 UTC 20 January (Fig. 18), the cyclone exhibits similar explosive characteristics as the "Dream Storm" of IOP 4. Over these 21 hours the cyclone moved northeast in the Atlantic off the Canadian maritime provinces (Fig. 19), and the central pressure of the cyclone dropped 34 mb to a minimum pressure of 965 mb, easily qualifying it as a "bomb". The track of this explosive storm can be seen in Fig. 20. Dissipation followed on 20 January as the central pressure began to rise.

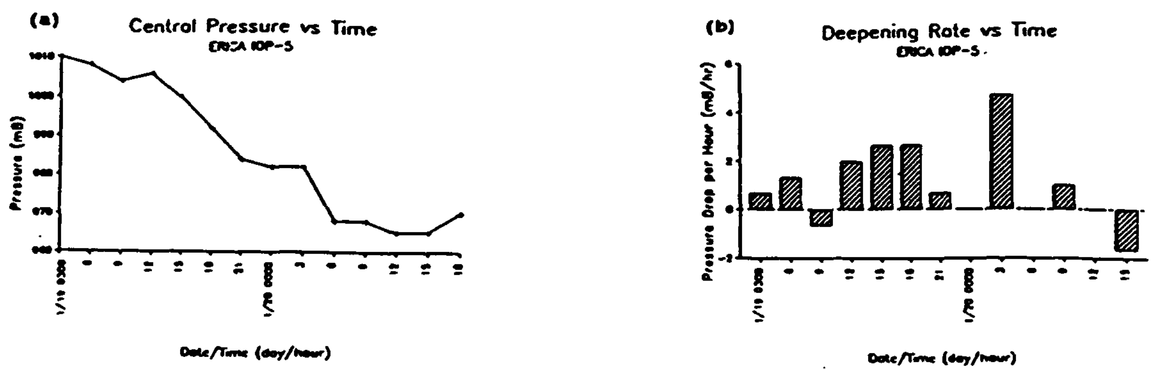


Figure 18. a) Central pressure (mb) vs time
b) Deepening rate (mb/hr) vs time for IOP 5

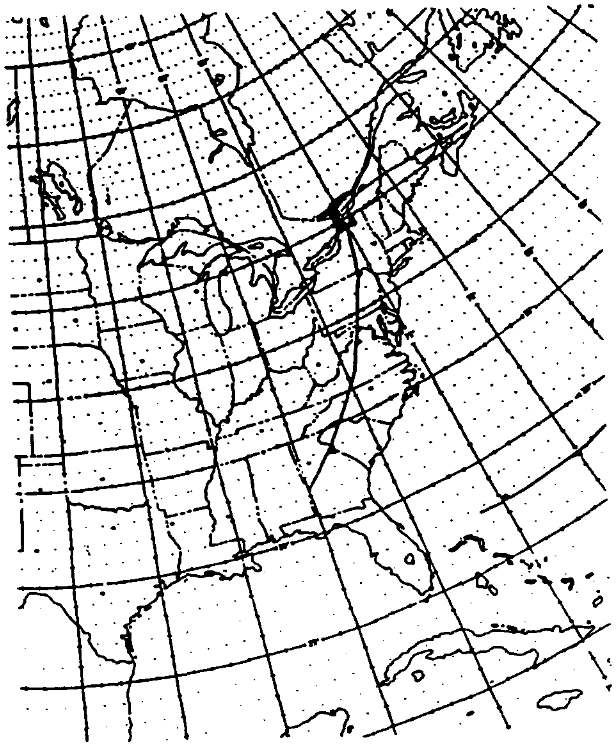


Figure 19. Surface analysis (0500 UTC 20JAN89)

Figure 20. Track of IOP 5 cyclone

The cyclones of IOP 4 and IOP 5 both developed into "bombs". The surface lows first appeared offshore east of Cape Hatteras in the region of a low pressure trough. Both cyclones moved northward along the warm side of the Gulf Stream current, where they deepened explosively. Movement continued northeastward as the cyclones intensified until they reached the North Atlantic where cyclone dissipation took place northeast of Nova Scotia. The role of the atmospheric lid as a precursor to explosive cyclogenesis will be examined in both storms.

C. LOP 6P

Midway through the field experiment, participants in ERICA found the data set containing several strong rapid deepeners, several marginal rapid deepeners, but no storm that could truly be called a non-developer and used as a comparison case. By the end of January the ERICA research team had become accustomed to studying only rapid deepeners. Thus, the task now put in the hands of the forecasters was to identify reasonable comparison cases. The case of 27 January 1989, LOP 6P, provided the non-explosive comparison storm that researchers were seeking.

At 0000 UTC 25 January (Fig. 21), two synoptic systems affected weather across the eastern third of the nation. First a surface low with a central pressure of 998 mb lay several hundred miles offshore of North Carolina. Secondly,

a frontal system associated with a low over the Canadian maritime provinces lay stationary through New England and back across the Midwest. Weather conditions over the southeastern states is dominated by high pressure centered over Tennessee. During the next 12 hours the Atlantic low has tracked well to the northeast, no longer affecting continental weather. The frontal system has swung southward and runs east-west from eastern Virginia through Missouri and southward into Texas. The front lies in a weak low pressure trough, located between two high pressure systems.

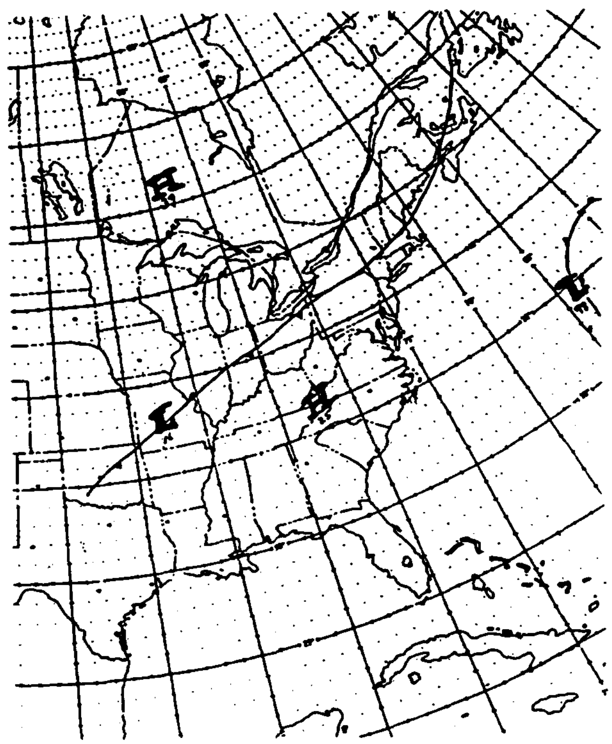


Figure 21. Surface analysis (0000 UTC 25JAN89)

At 1800 UTC 25 January (Fig. 22) the front has become stationary again and two waves can be seen along the front. A surface low, 1016 mb, is beginning to develop along the wave over Missouri. The second wave lies along the Virginia-North Carolina boarder. Over the next six hours the low pressure center continues to develop over the Midwest as it moves northward along the axis of a low pressure trough. The wave along the Eastern seaboard is more distinct, but a surface low is not yet identified. By

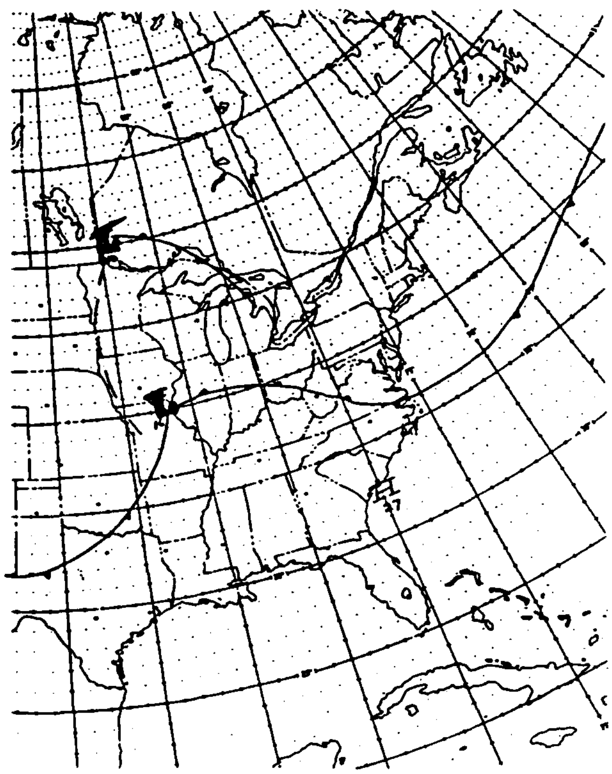


Figure 22. Surface analysis (1800 UTC 25JAN89)

1200 UTC 26 January (Fig. 23) the low has deepened to 1008 mb and lies over the Great Lakes region. The associated fronts extend southward along a strong low pressure trough. A second low pressure trough can also be seen over the mid-Atlantic coast. At 1800 UTC the same day, a wave developed along the warm front over southern Virginia. The low pressure trough was still present and lay slightly offshore.

However, during the hours to follow the synoptic situation took a dramatic turn. The surface analysis for

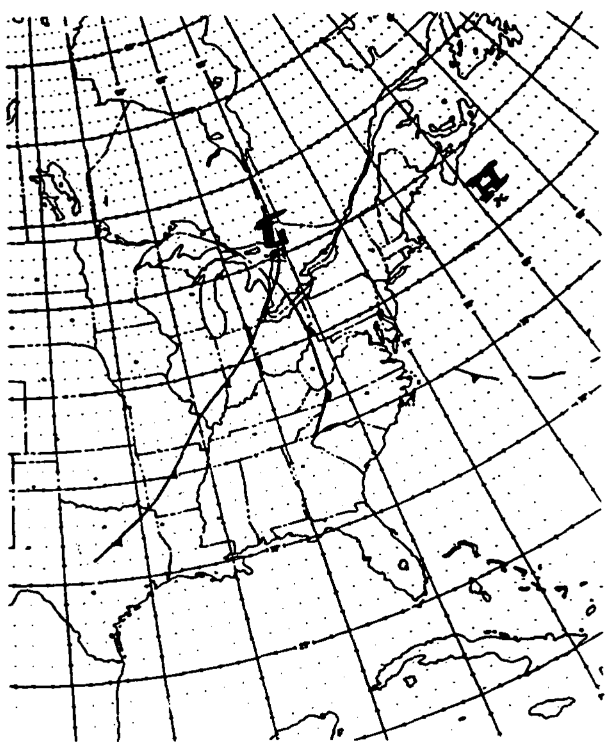


Figure 23. Surface analysis (1200 UTC 26JAN89)

0000 UTC 27 January (Fig. 24) shows that the warm front has moved dramatically northward and now lies across Northern New England. The low pressure trough offshore no longer exists, and high pressure now dominates the southeastern states and offshore. The cold front still extends north-south over the eastern third of the country.

During LOP 6P strong upper-level forcing associated with an upper-level trough and jet streak was present but failed to interact strongly with the low-level frontal

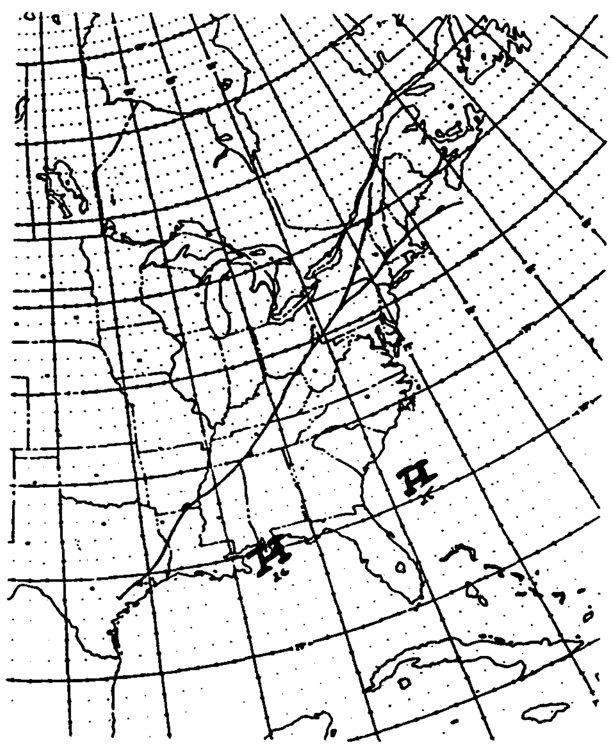


Figure 24. Surface analysis (0000 UTC 27JAN89)

system (Kreitzberg, 1990). Without this necessary interaction, no significant cyclogenesis took place, thus leaving ERICA scientists with the "comparison" case they needed. In this study LOP 6P will be used as a comparison case where the absence of the atmospheric lid will be examined.

IV. DISCUSSION OF RESULTS

A. IOP 4

The "Dream Storm" of IOP 4 first appeared on the NMC surface chart as an incipient surface low just off the coast of Cape Hatteras, NC at 0000 UTC 4 January 1989. As one of the deepest cyclones of the century, the IOP 4 storm provides an excellent case to test Green's hypothesis: the role of the atmospheric lid as a precursor for explosive marine cyclones. Green (1988) states that the atmospheric lid is present 12-48 hours prior to and located upwind of where the explosive cyclone develops.

From 0000 UTC 2 January through cyclone development, 12-hourly rawinsonde data from selected continental U.S. upper air observation sites in the region upwind of cyclone development were examined for the presence of an atmospheric lid. The continental rawinsonde data analyzed in this study, acquired from the ERICA Data Research Center (Drexel University in Philadelphia, PA), includes the following continental sites (See Fig. 25): Charleston, SC (72208); Cape Hatteras, NC (72304); Athens, GA (72311); Greensboro, NC (72317); Wallops Island, VA (72402); Dulles International Airport, VA (72403); Atlantic City, NJ (72407); Huntington, WV (72425); and Pittsburgh, PA (72520). During IOP evolution, data from Norfolk, VA (72308) and offshore points (999--) were also available at frequent intervals as well as selected continental sites from the list above. However,

the increased data collection began only six hours before the cyclone developed, and, therefore, was often not useful in examining the full lid condition at a particular site. Also, aircraft dropwinsonde data were often limited or flawed, and consequently not used in this study. Figure 25 shows the continental rawinsonde sites, and Fig. 26 shows aircraft dropwinsonde sites used in this study.

The soundings were analyzed using the GEMPAK/GEMPLT meteorological analysis software developed at the NASA Goddard Space Flight Center in Greenbelt, MD. If the

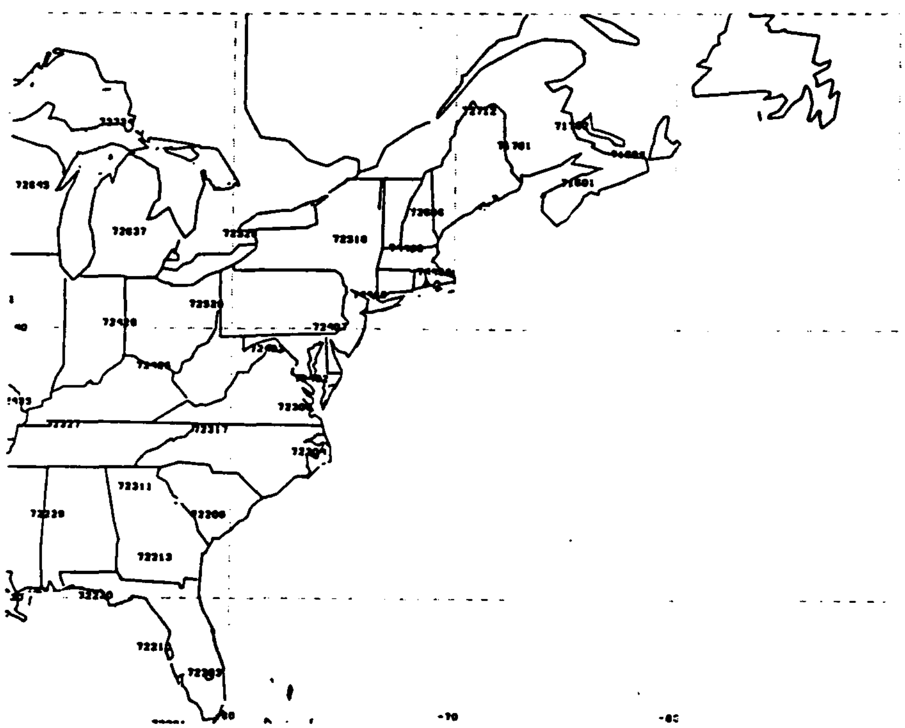


Figure 25. Continental sounding sites noted by five digit identifiers.

soundings met Green's criteria for an atmospheric lid (Chapter II), then lid strength values were calculated from the GEMPAK Skew-T, Log-P plots. Several "hand" calculated results from the plots were verified using software developed by Carlson at Pennsylvania State University. Due to incapatibility between the ERICA sounding files and Carlson's software, computer generated results were not available for all soundings. However, the results that were available verified those values calculated directly from the sounding plots.

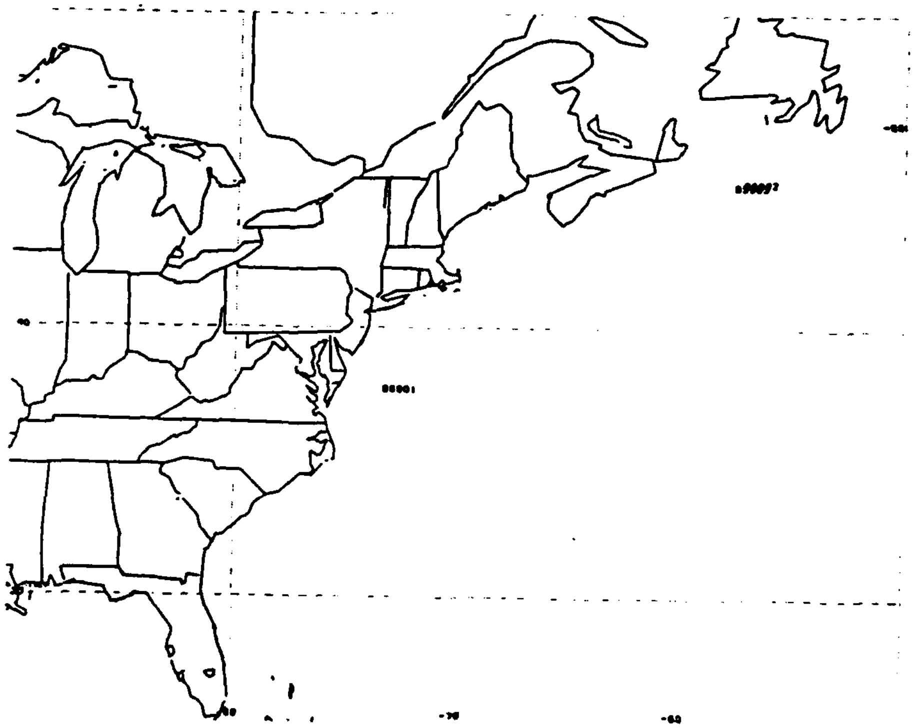


Figure 26. IOP 4 dropwinsonde sites noted by five digit identifiers (999xx) over ocean.

a)

STATION: CHS #72208 LAT: 32.90 LON: -80.03

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI	COMP
1/2	0000	no lid							-2.6
1/2	1200	850	6	18	19	12	13	25	23.9
1/3	0000	840	12	20	22	8	10	18	19.0
1/3	1200	840	7.5	17	17	9.5	9.5	19	21.3
1/4	0000	610	16	16	16	0	0	0	.7
1/4	0600	frontal							

b)

STATION: HAT #72304 LAT: 35.27 LON: -75.55

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI	COMP
1/2	0000	780	8	16	17	8	9	17	15.5
1/2	1200	830	5	16	17.5	11	12.5	23.5	22.0
1/3	0000	880	7.5	18	18	10.5	10.5	21	
1/3	1200	790	7	14.5	13	7.5	6	13.5	
1/3	1800	780	6	14.5	13	8.5	7	15.5	
1/4	0000	no lid							
1/4	0600	no lid							

c)

STATION: ORF #72308 LAT: 36.90 LON: -76.19

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/3	1800	850	3	13	11	10	8	18
1/3	2100	frontal						
1/4	0000	frontal						
1/4	0900	no lid						
1/4	1200	no lid						
1/4	1500	no lid						

d)

STATION: AHN #72311 LAT: 33.95 LON: -83.32

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/2	0000	780	7	18	19	11	12	23
1/2	1200	850	5	17	17	12	12	24
1/3	0000	900	8.5	19	18.5	10.5	10	20.5
1/3	1200	875	10.2	17	17	7.2	7.2	14.4
1/3	1800	no lid						
1/4	0000	frontal						
		640	10	17	17	7	7	14

Table 1(a-d) IOP 4 lid strength calculations for selected East Coast rawinsonde stations. Date and Time are expressed as UTC; HLID is the height of the lid base (mb); θ_w, θ_{sw5}, and θ_{sw1} (°C) as defined in Ch II; Buoy is the Buoyancy Term (°C); LID is the Lid Strength Term (°C); LSI is the Lid Strength Index (°C) calculated by hand; COMP is the computer generated values of LSI.

e)

STATION: WAL #72402 LAT: 37.93 LON: -75.48

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI	COMP
1/2	0000	770	6	14	12.5	8	5.5	13.5	
1/2	1200	800	4	14	12.5	10	7.5	17.5	20.5
1/2	1500	800	3	14	14	11	11	22	24.0
1/2	1800	760	4	14	14	10	10	20	19.9
1/3	0000	800	6	16	16	10	10	20	
1/3	1200	825	2	11	10	9	8	17	
1/3	1800	840	1	11.5	10	10.5	9	19.5	
1/3	2100	several							
1/4	0000	frontal							
1/4	0300	frontal							
1/4	0600	no lid							

f)

STATION: IAD #72403 LAT: 38.98 LON: -77.47

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI	COMP
1/2	0000	670	0	14	14	14	14	28	26.8
1/2	1200	740	2	13	13	11	11	21	21.7
1/2	1500	820	1	12.5	11	11.5	10	21.5	20.9
1/2	1800	720	2.5	13	12	10.5	9.5	20	20.5
1/3	0000	800	5	14	12	9	7	16	
1/3	1200	840	-2	11	10	13	12	25	27.2
1/3	1800	800	-1	10	8	11	9	20	
1/3	2100	800	2	8	6	6	4	10	
1/4	0000	frontal							
1/4	0300	no lid							
1/4	0600	no lid							
1/4	0900	no lid							

g)

STATION: GSO #72317 LAT: 36.08 LON: -79.94

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/2	0000	820	4	16	17	12	13	25
1/2	1200	850	5	15	15	10	10	20
1/3	0000	900	5	14	13	9	8	17
1/3	1200	several						
1/3	1800	860	7.5	14	15	6.5	7.5	14
1/4	0000	no lid						
1/4	0600	no lid						

Table 1(e-g) IOP 4 lid strength calculations (cont.)

h)

STATION: ACY #72407 LAT: 39.75 LON: -74.67

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/2	0000	690	2.5	13	12.5	10.5	10	20.5
1/2	1200	several						
1/3	0000	750	1	12	10	11	9	20
1/3	1200	770	-2	9.5	8.5	11.5	10.5	22
1/3	1800	780	-2	10	9	12	11	23
1/3	2100	790	-4	10	8	14	12	26
1/4	0000	870	-8	6	2	14	10	28
1/4	0300	frontal						
1/4	0600	no lid						
1/4	0900	no lid						

i)

STATION: HTS #72425 LAT: 38.37 LON: -82.55

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/2	0000	680	2.5	12.5	12.5	10	10	20
1/2	1200	800	2	12	11	10	9	19
1/3	0000	770	5	14	13	9	8	17
1/3	1200	900	0	9	6	9	6	15
1/4	0000	no lid						

j)

STATION: PIT #72520 LAT: 40.53 LON: -80.23

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/2	0000	680	2.5	12.5	12.5	10	10	20
1/2	1200	several						
1/3	0000	700	0	11	10	11	10	21
1/3	1200	860	-4	6.5	2	10.5	6	16.5
1/4	0000	no lid						

k)

STATION: #99901 LAT: 37.50 LON: -71.69

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/3	1953	850	6	11	8	5	2	7
		600	6	13	13	7	7	14
1/3	2039	740	2	10	10	8	8	16
1/3	2141	840	-2	4	1	6	3	9

Table 1(h-k). IOP 4 lid strength calculations (cont.)

Looking upwind 48 hours prior to cyclone development, 0000 UTC 2 January, an atmospheric lid clearly is present at the continental sounding sites upwind of cyclone development. Tables 1(a-j) show the lid information for the continental rawinsonde sites. Lid Strength Index (LSI) values ranged from zero to 28, and Charleston was the only station with no lid present. Over the next 12 hours, the lid remained, and at most stations LSI values increased to their highest values. After peaking around 1200 UTC 2 January, the LSI values began to gradually fall until either no lid was present, or frontal inversions masked lid strength calculations. By 0000 UTC 4 January when the incipient stage of the cyclone was first noted, all LSI values where either zero, no lid present, or had been replaced by frontal inversions.

Cape Hatteras, station #72304, provides an excellent example of the presence of an atmospheric lid condition. The 0000 UTC sounding data on 2 January shows a lid with an LSI value of 17. Similar to the other sites, Hatteras experiences a maximum LSI value at 1200 UTC of the same day. The atmospheric lid condition is clearly visible in Fig. 27. On this plot, the sharp temperature increase and coincident dewpoint decrease are clearly visible between 900 and 850 mb. Over the next 36 hours the LSI values decrease until 0000 UTC 4 January when no lid is present on the sounding plot (Fig. 28).

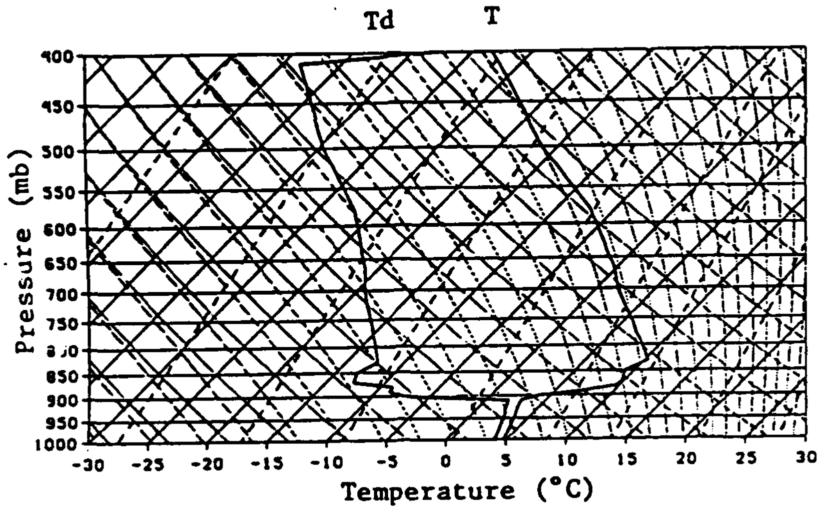


Figure 27. #72304 sounding (1200 UTC 2JAN89). Vertical axis is pressure (mb) with isotherms as solid lines sloping from lower left to upper right; dashed lines are saturation mixing ratio lines representing saturated values of moisture content. The sounding to the left is the vertical dewpoint temperature while that to the right is temperature.

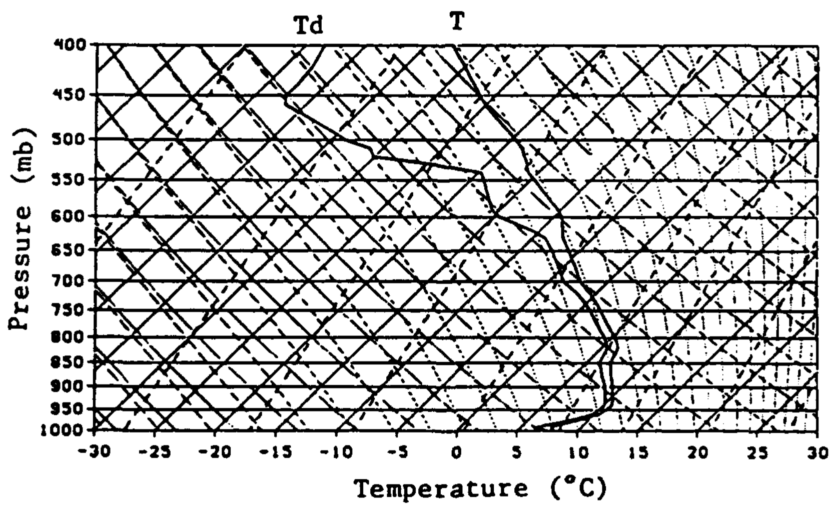


Figure 28. #72304 sounding (0000 UTC 4JAN89)

Continental sounding sites were not the only stations to exhibit atmospheric lid conditions. Dropwinsondes released over the ocean from research aircraft provided data to be analyzed. The sounding (Fig. 29) from station #99901 (37.50 N, 71.69 W) also shows a lid condition to be present (Table 1k). This site is located just offshore of Cape Hatteras and has similar LSI values. Data were taken at this station three times over a two hour period beginning at 2039 UTC 3 January. During this time, LSI values experienced a downward trend, as did the Hatteras site

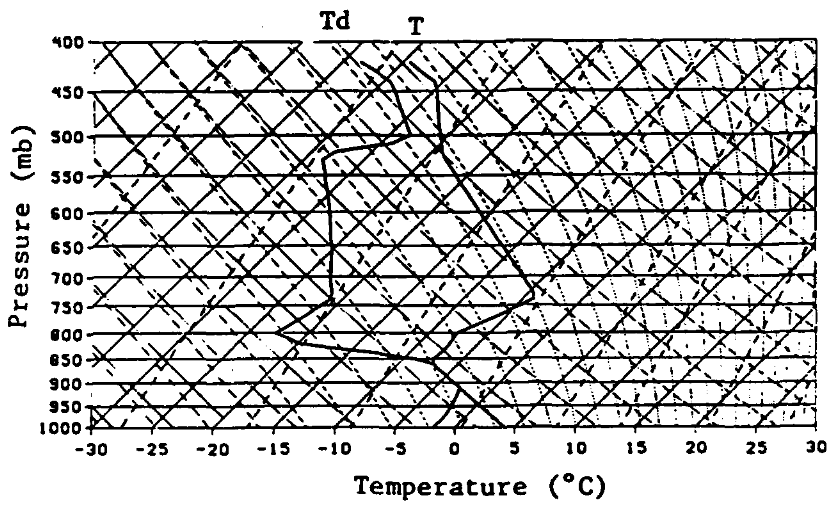


Figure 29. #99901 sounding (2309 UTC 3JAN89)

during the same period. Data at the time of cyclone development were not available at this location. The inversion can be seen between 850 and 800 mb. However, this lid is interrupted at 800 mb by a frontal inversion. Thus, the actual LSI value at this time may be greater than the calculated value of 7.

The above results show that an atmospheric lid condition clearly existed prior to explosive cyclogenesis during IOP 4, and may contribute to the explosive intensification of this storm. When present, an atmospheric lid actually suppresses convection. Beneath it, the lid traps the moist, unstable air and prevents it from rising and releasing its energy. The higher the Lid Strength Index value, the stronger the inversion, and the more energy that is trapped below the lid. At some point the unstable air either transits from under the lid or overcomes it. In either case, the result is the same. Immense amounts of energy are released at one time into the developing cyclone, causing it to deepen at such an explosive rate as the IOP 4 cyclone did.

B. IOP 5

The explosively developing cyclone of IOP 5 first appeared as a surface low pressure center at 0300 UTC 19 January and is referred to as the "Sleeper", due to its delayed rapid deepening. Similar to the examination of the

atmospheric lid condition in IOP 4, the search for the lid began at 0000 UTC 17 January, 48 hours before cyclone development. Rawinsonde data were taken from the same continental sites as IOP 4 (Fig. 25) at 12 hour intervals until increased data collection began at 1800 UTC 18 January. At this time limited dropwinsonde data from aircraft were also available for analysis (Fig. 30) Utilizing the GEMPAK/GEMPLT software, the sounding plots were analyzed for the presence of the atmospheric lid. If present, LSI values were determined using the sounding plots.

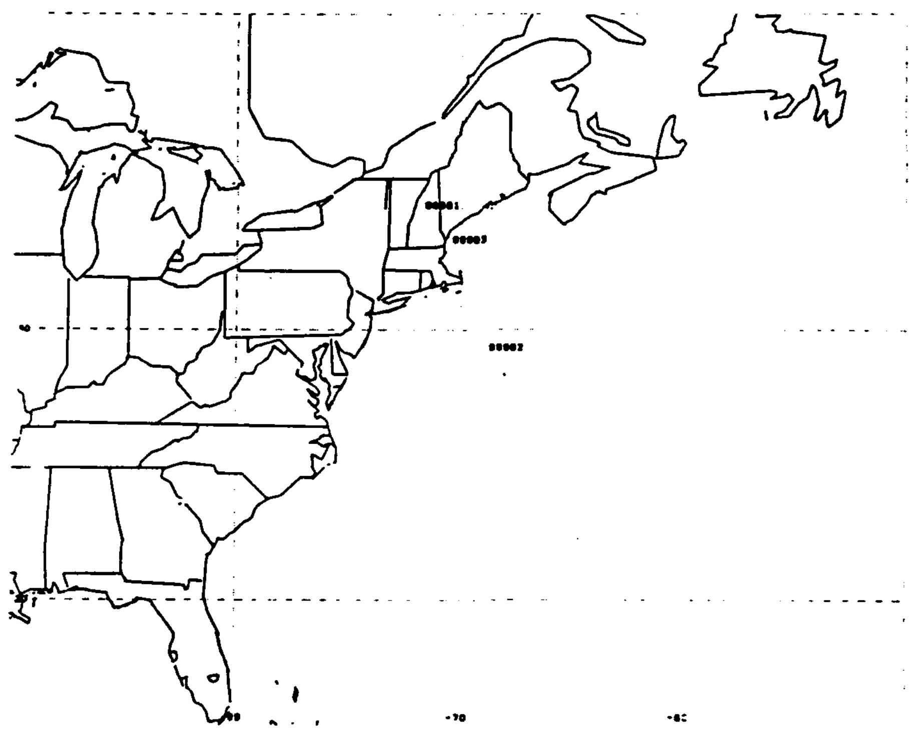


Figure 30. IOP 5 dropwinsonde sites

a) STATION: CHS #72208 LAT: 32.90 LON: -80.03

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/17	0000	770	7	17.5	16	10.5	1.5	11.5
1/17	1200	850	4	16	12	12	8	18
1/18	0000	800	7	15	15	8	8	16
1/18	1200	830	5	16	14	11	9	20
1/18	1800	frontal						
1/19	0000	no lid						
1/19	0600	frontal						

b) STATION: HAT #72304 LAT: 35.27 LON: -75.55

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/17	0000	frontal						
1/17	1200	frontal						
1/18	0000	frontal						
1/18	1200	730	2	14	14	12	12	24
1/18	1800	720	7	14	13	7	6	13
1/18	2100	790	6	14	14	8	8	16
1/19	0000	820	5	15	14	10	9	19
1/19	0900	no lid						

c) STATION: ORF #72308 LAT: 36.90 LON: -76.19

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/18	1800	frontal						
1/19	0000	no lid						

d) STATION: AHN #72311 LAT: 33.95 LON: -83.32

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/17	0000	850	4	16	11	12	5	17
1/17	1200	frontal						
1/18	0000	860	4	15	12	11	8	19
1/18	1200	800	0	15	14	15	14	29
1/18	1800	720	4	16	14	12	10	22
1/19	0000	700	6	15	16	9	10	19
1/19	0600	frontal						

Table 2(a-d). IOP 5 lid strength calculations

e) STATION: GSO #72317 LAT: 36.0[illegible] LON: -79.94

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	800	-1	12	9	13	10	23
1/17	1200	830	-3	12	7	15	10	25
1/18	0000	850	2	14	10	12	8	20
		730	2	14	13	12	11	23
1/18	1200	930	0	13	10	13	10	13
1/18	1800	frontal						
1/19	0000	frontal						
1/19	0600	frontal						

f) STATION: WAL #72402 LAT: 37.93 LON: -75.48

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	frontal						
1/17	1200	780						
1/18	0000	710	2	13	13	11	11	22
1/18	1200	700	2	13	12	11	10	21
1/18	0000	no lid						
1/19	0000	no lid						

g) STATION: IAD #72403 LAT: 38.98 LON: -77.47

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	frontal						
1/17	1200	550	-1	10	10	11	11	22
1/18	0000	700	3	13	11	10	8	18
1/18	1200	700	3	13	10	11	7	18
1/18	1800	750	2	13	10	11	8	19
1/18	2100	no lid						
1/19	0000	no lid						
1/19	0600	no lid						

Table 2(e-g). IOP 5 lid strength calculations

h) STATION: ACY #72407 LAT: 39.75 LON: -74.67

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	frontal						
1/17	1200	630	-3	10	8	13	11	24
1/18	0000	770	1	13	8	12	7	19
1/18	1200	700	2	13	10	12	8	20
1/18	1800	860	3	13	9	10	6	16
1/18	2100	no lid						
1/19	0000	frontal						
1/19	0600	no lid						
1/19	0900	no lid						

i) STATION: HTS #72425 LAT: 38.37 LON: -82.55

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	frontal						
1/17	1200	600	-1	12	11	13	12	25
1/18	0000	650	3	13	14	10	11	21
1/18	1200	640	0	14	15	14	15	29
1/18	1800	800	4	12	11	8	7	15
1/19	0000	no lid						

j) STATION: PIT #72520 LAT: 40.53 LON: -80.23

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/17	0000	no lid						
1/17	1200	frontal						
1/18	0000	630	2	12	11	10	9	19
1/18	1200	920	2	12	7	10	5	15
1/18	1800	840	4	12	9	8	5	13

k) STATION: #99902 LAT: 39.07 LON: -67.01 ELE

DATE	TIME	HLID	θw	$\theta sw5$	$\theta sw1$	BUOY	LID	LSI
1/18	0615	no lid						

Table 2(h-k). IOP 5 lid strength calculations

At 0000 UTC 17 January, the atmospheric lid was visible at several of the continental rawinsonde sites [Table 2(a-k)]. However, at the majority of the sites, the search for the lid condition was obscured by the presence of frontal inversions. Over the next 36 hours, in the absence of frontal inversions, the lid condition could be seen in the sounding plots. Close to the beginning of cyclone development, the atmospheric lid condition was gone. Either no lid was present, or a frontal inversion had replaced the previously existing lid. However, unlike the IOP 4 results, LSI values did not reach a decisive peak. The values fluctuated slightly at the different continental sites, with many frontal inversions affecting the atmospheric lid evaluation.

Cape Hatteras again exhibits the lid condition (Fig. 31) in the analyzed rawinsonde data before rapid deepening of the IOP 5 cyclone. Unlike the IOP 4 case, the LSI values do not reach a maximum 36 hours before development. Rather, the highest LSI value is seen at 1200 UTC 18 January, less than 24 hours prior to cyclone development. The lid condition gradually weakens after its peak until it is no longer present on the 0900 UTC 19 January plot.

Aircraft dropwinsonde data were examined for this case (Table 2k), but were not found to be useful in this study. When searching for the atmospheric lid, it is necessary to look upwind of cyclone development. The dropwinsonde data

collected during this period was either too far out to sea or after initial cyclone deepening had occurred. Thus, it is necessary to consider only continental rawinsonde data during this case.

During the IOP 5 investigation, the atmospheric lid was clearly present 36 hours prior to, but had disappeared by the time of cyclone explosive development. These results are similar to those observed in IOP 4, although, differences between the two cases are evident. First, maximum LSI values occurred later and were lesser in magnitude during

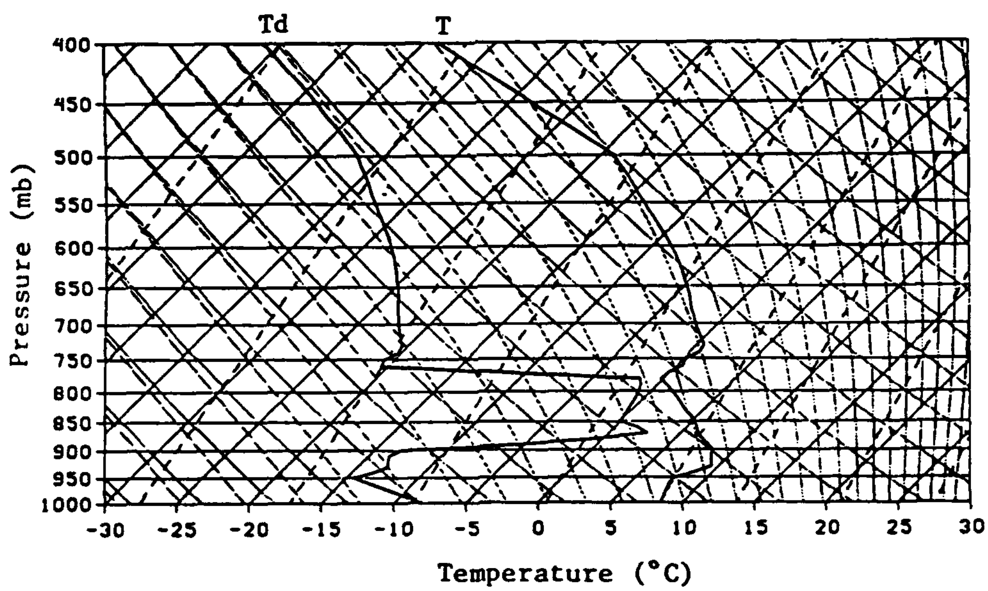


Figure 31. #72304 sounding (1200 UTC 18JAN89)

IOP 5. Also, IOP 5 provided lids that were not as clearly defined nor as consistent as during IOP 4. Lastly, IOP 5 data results were masked by the presence of frontal inversions which may be the cause of decreased consistency among LSI values.

C. LOP 6P

The case of 27 January 1989, LOP 6P, provides the control case for this study. During this case, an explosively developing cyclone failed to develop despite atmospheric conditions that favor cyclone development. As with the explosive storms, 12-hourly continental rawinsonde data (Fig. 25) were considered over the period 0000 UTC 25 January to 1200 UTC 27 January for the presence of the atmospheric lid.

During this period, the presence of lids and corresponding LSI values varied greatly among the different sounding sites. Some sites showed single lids, others with very weak lids, and the rest exhibited no lid condition at all [Table 3(a-i)]. If a lid condition was present during this period, it was usually only visible in one of the six soundings evaluated at each station. Still, even if an LSI value were calculated, it was much less than in previously studied cases.

a) STATION: CHS #72208 LAT: 32.90 LON: -80.03

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	no lid						
1/25	1200	frontal						
1/26	0000	frontal						
1/26	1200	880	13	16	15	3	2	5
1/27	0000	820	12	17	17	5	5	10
1/27	1200	no lid						

b) STATION: HAT #72304 LAT: 35.27 LON: -75.55

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	no lid						
1/25	1200	no lid						
1/26	0000	no lid						
1/26	1200	frontal						
1/27	0000	850	12	16	17	4	5	9
1/27	1200	no lid						

c) STATION: AHN #72311 LAT: 33.95 LON: -83.32

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	frontal						
1/25	1200	no lid						
1/26	0000	no lid						
1/26	1200	850	8	16	17	8	7	15
1/27	0000	770	14	17	17	3	3	6
1/27	1200	frontal						

d) STATION: GSO #72317 LAT: 36.08 LON: -79.94

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	no lid						
1/25	1200	no lid						
1/26	0000	650	9	15	15	6	6	12
1/26	1200	no lid						
1/27	0000	800	11	15	16	4	5	9
1/27	1200	frontal						

Table 3(a-d). LOP 6P lid strength calculations

e) STATION: WAL #72402 LAT: 37.93 LON: -75.48

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	frontal						
1/25	1200	no lid						
1/26	0000	620	3	15	14	12	11	23
1/26	1200	no lid						
1/27	0000	no lid						

f) STATION: IAD #72403 LAT: 38.98 LON: -77.47

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	frontal						
1/25	1200	no lid						
1/26	0000	no lid						
1/26	1200	860	1	14	13	13	12	25
1/27	0000	no lid						

g) STATION: ACY #72407 LAT: 39.75 LON: -74.67

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	no lid						
1/25	1200	910	1	13	9	12	8	20
1/26	0000	no lid						
1/26	1200	no lid						
1/27	0000	frontal						

h) STATION: HTS #72425 LAT: 38.37 LON: -82.55

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	0000	no lid						
1/25	1200	730	7	14	14	7	7	14
1/26	0000	no lid						
1/26	1200	820	9	15	14	6	5	11
1/27	0000	no lid						

i) STATION: PIT #72520 LAT: 40.53 LON: -80.23

DATE	TIME	HLID	θ_w	θ_{sw5}	θ_{sw1}	BUOY	LID	LSI
1/25	1200	no lid						
1/26	0000	no lid						
1/26	1200	no lid						
1/27	0000	frontal						
1/27	1200	no lid						

Table 3(e-i). LOP 6P lid strength calculations

Cape Hatteras exhibits no visible lid in the sounding plot of 0000 UTC 25 January (Fig. 32) . Over the next 48 hours, no atmospheric lid develops. Only the 0000 UTC 27 January sounding shows any signs of an atmospheric lid. However, the lid present at this time has only an LSI value of 9, and is gone by the next 12 hour sounding. Thus, it is clear that the Hatteras soundings for this case varied greatly from those of the two previous IOP's, with no clear cut evidence of a lid condition.

Three cases of the ERICA field project were examined above for the presence of the atmospheric lid condition as described by Green (1988). Data from both IOP 4 and 5 support Green's hypothesis, for they clearly display the presence of the atmospheric lid prior to the explosive development of the cyclone. In contrast, LOP 6P did not show the atmospheric lid condition prior to the expected time of rapid deepening, thus serving as the comparison case for this study and supporting Green's theory.

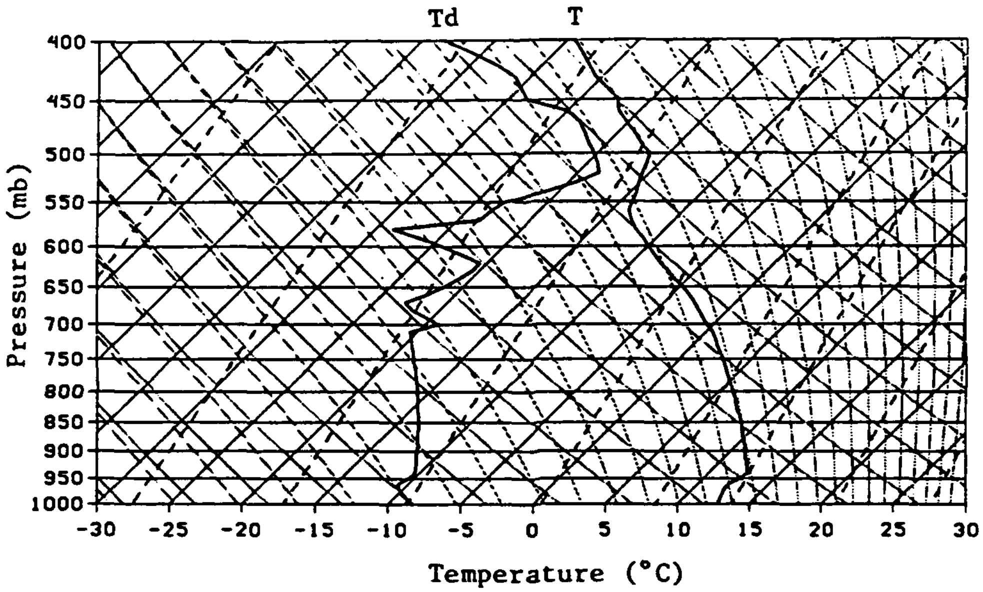


Figure 32. #72304 sounding (0000 UTC 25JAN89)

V. MODEL INPUT

Meteorologists rely heavily on National Meteorological Center (NMC) numerical weather prediction models, such as the Nested Grid Model (NGM), to forecast atmospheric conditions. However, operational numerical models often fail to predict the development, intensification, and storm track of explosive cyclones adequately. Deepening rates predicted by operational dynamical models fall far short of the observed ones, implying that some physical effect other than commonly understood large-scale baroclinic mechanisms may play an important role (Sanders, 1980). The failure of numerical models to simulate explosive cyclogenesis accurately may result from the lack of data used to define the initial conditions and from inadequate parameterization of physical processes in the model (Manobianco, 1989).

The NGM model offers a potential tool for understanding the atmospheric lid theory. First, in order to know where to search for the lid condition, one must know when and where a cyclone is expected to develop. NGM output provides sounding data from any geographical location to be analyzed. Thus, atmospheric soundings offshore could be searched for the presence of an atmospheric lid in addition to regular rawinsonde sites, without relying on aircraft dropwinsondes.

During this study comparisons between soundings from NGM model output and actual rawinsonde data were performed to view the atmospheric lid condition in each case. Figure

33a shows the rawinsonde sounding for Cape Hatteras at 0000 UTC 3 January, 1989 while Fig. 33b displays the sounding from NGM model output for Hatteras at the same time. The difference between the two soundings is evident. Although the NGM sounding does indicate a lid condition, it is not as clearly defined as in the actual rawinsonde sounding. The inversion in the NGM sounding is weaker and extends over 100 mb while the actual lid is present over only 50 mb. Also, the LSI value (17) in the NGM plot is less the observed value (21). A second station, Wallops Island, VA was also compared to model output. Again, the lid in the NGM plot is weaker [Fig. 34(a-b)]. In fact, it exhibits no true inversion. This comparison explicitly shows that the NGM model does not accurately depict the atmospheric lid condition and, thus, in its current form is not reliable for computing LSI values. However, the model may still be used in a limited fashion to determine the possible presence of the lid condition.

No physical factor critical for marine cyclogenesis is missing in the NGM model as it now stands. Hence, explosive cyclogenesis over the sea is not a complete mystery, in the sense that models are incapable of dealing with the phenomena (Sanders, 1987). The research problem facing the meteorological community is to improve the skill of the model, to extend the range of predictability of cyclogenesis, and to increase the accuracy, especially with

cyclogenesis, and to increase the accuracy with which the NGM model represents atmospheric lids. If such corrections are implemented, the ability of the NGM model to handle explosively developing cyclones will be much improved, hence providing forecasters with a better tool for predicting this phenomena.

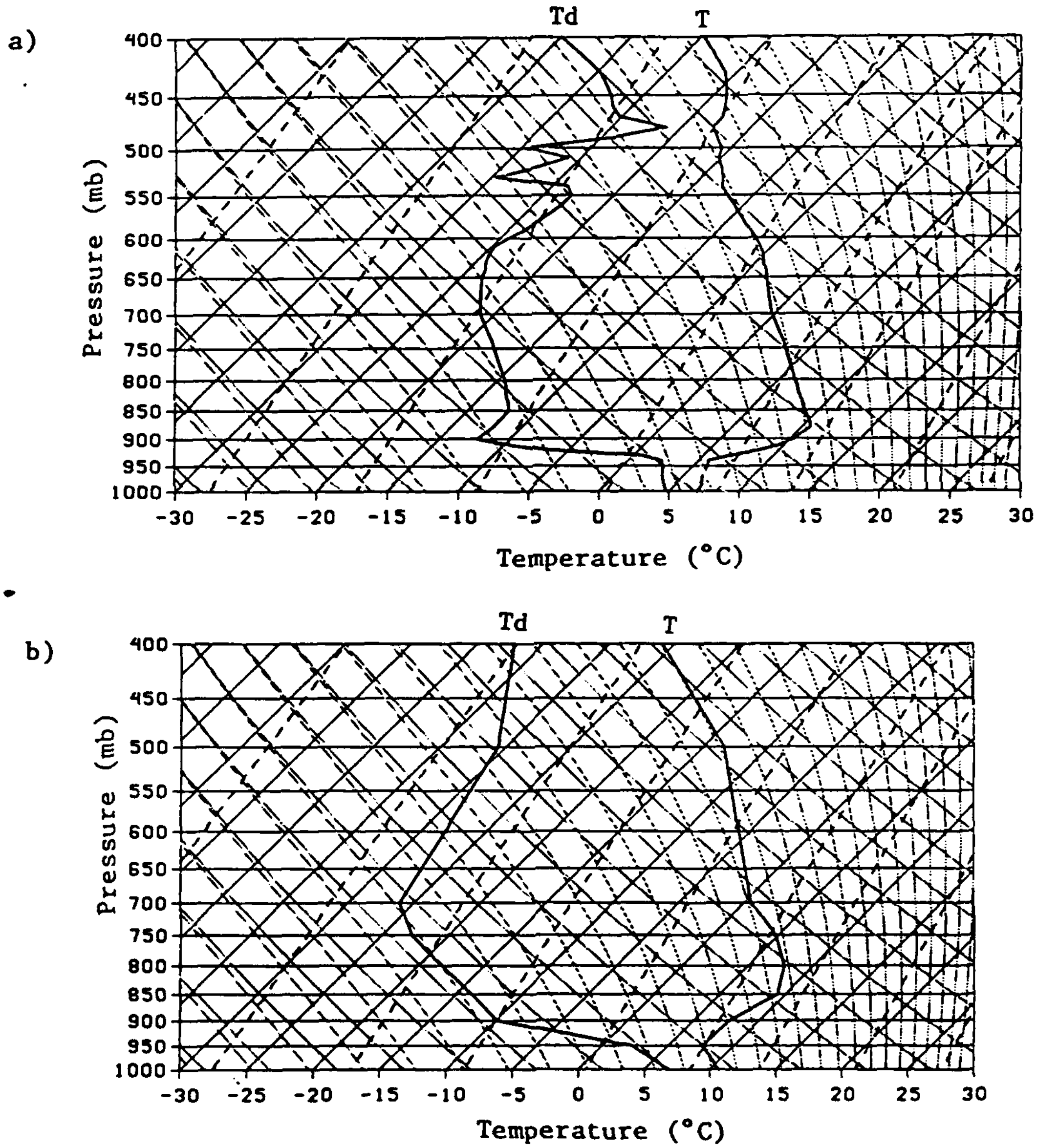
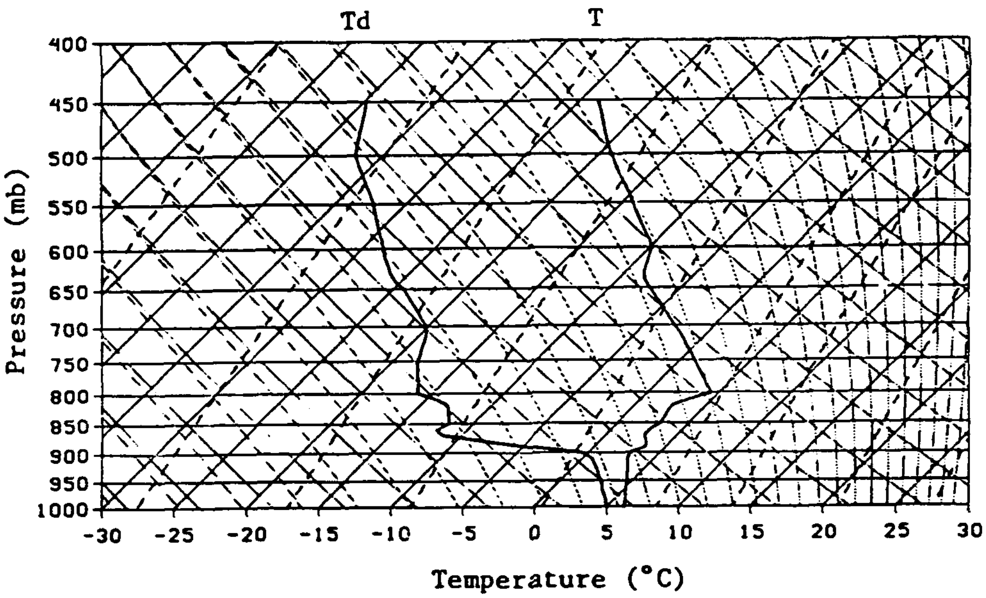


Figure 33. a) Actual sounding for #72304 (0000 UTC 3JAN89)
b) NGM sounding for #72304 (0000 UTC 3JAN89)

a)



b)

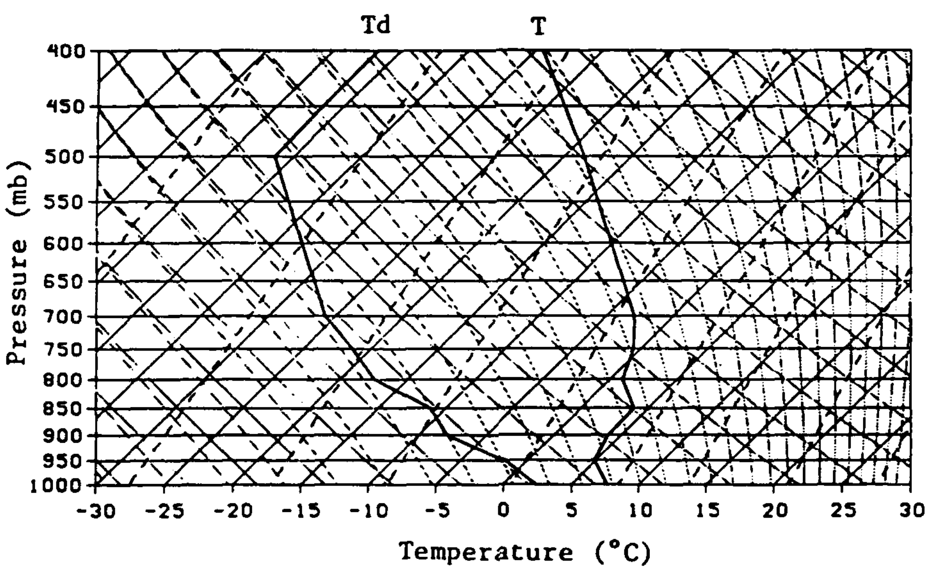


Figure 34. a) Actual sounding for #72402 (0000 UTC 3JAN89)
b) NGM sounding for #72402 (0000 UTC 3JAN89)

VI. CONCLUSIONS

This study suggests that the atmospheric lid condition as defined by Green (1988) may be a precursor to explosive cyclogenesis. Results show that 36-48 hours prior to explosive cyclone development, a lid condition can be identified in upper air soundings at sites upwind of cyclone development. The lid disappears prior to rapid cyclone deepening, resulting in the release of large amounts of energy stored beneath the lid, thereby enhancing cyclone development. Lid conditions existed during ERICA IOP 4 and 5 prior to explosive cyclone development. In the study of ERICA LOP 6P, no substantial lid condition was observed. These findings in conjunction with the results of Green's study on two GALE storms clearly support Green's hypothesis.

The NGM model can be beneficial as a forecasting tool for explosive cyclogenesis. Model output can be used to identify the expected time and location for cyclone development. Given, the most likely temporal and spatial positions predicted by the model, locations can be selected to test for lid strength. With improved vertical resolution within the model, magnitudes of LSI can then be computed to determine whether the cyclone might develop explosively or not.

Each winter, explosive marine cyclones are responsible for heavy precipitation, gale-force winds, and violent sea states. Currently these storm come without adequate

warning, causing serious damage along the eastern seaboard of the United States. Green's hypothesis (1988) suggests that the atmospheric lid may constitute a precedent signature for explosive marine cyclogenesis that can eliminate the surprise factor of these events, resulting in a reduction of lives lost and property damaged during such storms.

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